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Coherent Electron Focussing in a Two-Dimensional Electron Gas.

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Abstract. – The first experimental realization of ballistic point contacts in a two-dimensional electron gas for the study of transverse electron focussing by a magnetic field is reported. Multiple peaks associated with skipping orbits of electrons reflected specularly by the channel boundary are observed. At low temperatures fine structure in the focussing spectra is seen.

Introduction. – Classical and quantum-mechanical transport in two-dimensional electron gases (2DEG) is mostly studied in the diffusive regime, *i.e.* on length scales large compared to the transport mean free path l. Due to the recent availability of high-mobility GaAs-AlGaAs heterostructures, l can be as large as 10 μm. With micro-fabrication technology it is now becoming feasible to make structures for the study of electron transport which are much smaller than l. In such structures the electron motion is ballistic. From metal physics, where l is of the order of 1 mm in single crystals, it is known that ballistic transport can ideally be studied employing Sharvin-point contacts [1], *i.e.* constriction-type contacts with width $W \ll l$, but much larger than the Fermi wavelength $\lambda_F \equiv 2\pi/k_F$ (in metals $\lambda_F \sim 0.5$ nm). Such classical point contacts can be used to inject electrons at or above the Fermi energy, thereby allowing the study of elastic and inelastic scattering processes. This field is known as point contact spectroscopy [2, 3]. Longitudinal or transverse electron focussing (TEF) by a magnetic field can be observed with, respectively, two opposite (Sharvin [1]) or adjacent (Tsoi [4]) point contacts, serving as injector and collector. Electron surface scattering [5] can be investigated by measuring the amplitudes of subsequent peaks in the transverse focussing spectrum due to repeated specular reflections from the boundaries. This in itself would be a sufficient reason to study point contacts in a 2DEG. Moreover, since $\lambda_F \sim 40$ nm in the 2DEG, this opens the fascinating possibility to fabricate point contacts with dimensions close to λ_F. We could call these *quantum point contacts*.

In this letter the first experimental realization of point contacts for a study of TEF in a two-dimensional electron gas is reported.

Split-gate variable point contacts. – We have fabricated point contacts in a 2DEG in a GaAs-AlGaAs heterostructure with carrier concentration $n_s = 3.5 \cdot 10^{15}\,\mathrm{m}^{-2}$ and mobility $\mu = 90\,\mathrm{m}^2/\mathrm{V\,s}$, leading to a transport mean free path $l \sim 9\,\mu\mathrm{m}$. A standard mesa-etched Hall-bar geometry has been chosen as a starting point. Constrictions in the 2DEG in this Hall-bar have been defined using a split-gate geometry, schematically indicated in fig. 1.

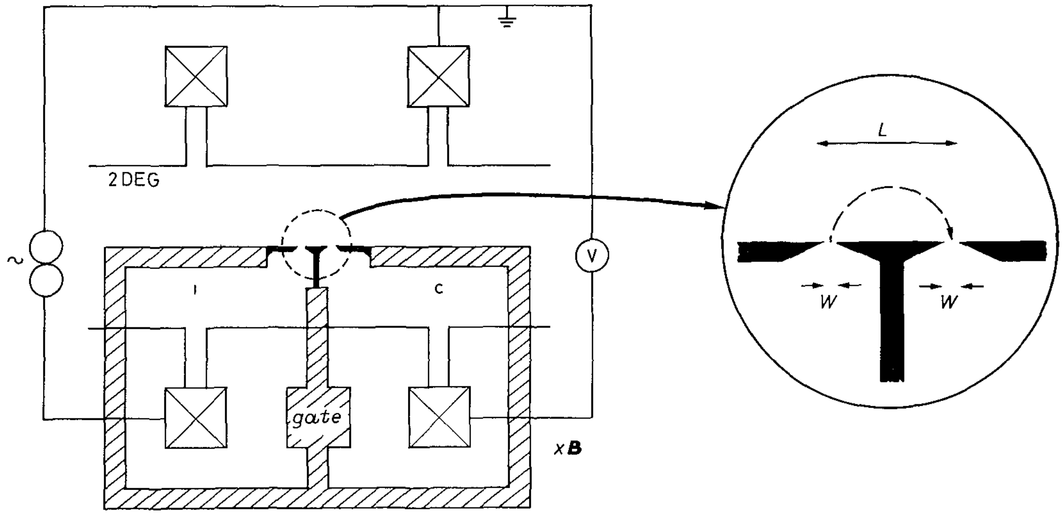

Fig. 1. – Schematic layout of the split gate (dashed area) double-point contact structure for the TEF-experiments. The crossed squares are ohmic contacts to the 2DEG. The gate divides injector (i) and collector (c) areas from the bulk 2DEG. The dashed line indicates an electron trajectory in a magnetic field.

Electron-beam lithography is used to write the fine details of the gate structure. The split-gate technique has been used earlier by Thornton *et al.* [6] and Zheng *et al.* [7] for the study of narrow conducting channels. By increasing the (negative) voltage on the Schottky gate the electron gas underneath the gate structure is depleted. Beyond the depletion threshold (typically 0.6 V), no mobile carriers are present under the gate, and two conducting constrictions are formed with a width of about 250 nm. A further increase of the gate voltage forces both constrictions to become progressively narrower, until they are fully pinched off. By this technique it is possible to define point contacts with variable width. One of the contacts can be used as a ballistic electron injector, while the other point contact acts as a collector for the electrons which are focussed by a magnetic field. As discussed below, the width of the point contacts can be obtained from the conductance.

Experimental results. – In fig. 2 the collector voltage as a function of magnetic field is shown for a device with $3.0\,\mu\mathrm{m}$ point contact separation, for temperatures between 30 mK and 4 K. At the higher temperatures a clear set of equidistant peaks is observed, associated with multiple specular reflection from the 2DEG boundary (see inset). Classically, the peaks in the collector voltage are expected to occur at values of the magnetic field which obey the condition that the point contact separation L is an integer multiple of the classical cyclotron orbit diameter $d_{\mathrm{cycl}} = 2v_{\mathrm{F}}/\omega_{\mathrm{c}}$, or

$$B^{\max} = i\frac{2\hbar k_{\mathrm{F}}}{eL}, \qquad i = 1, 2, \ldots . \tag{1}$$

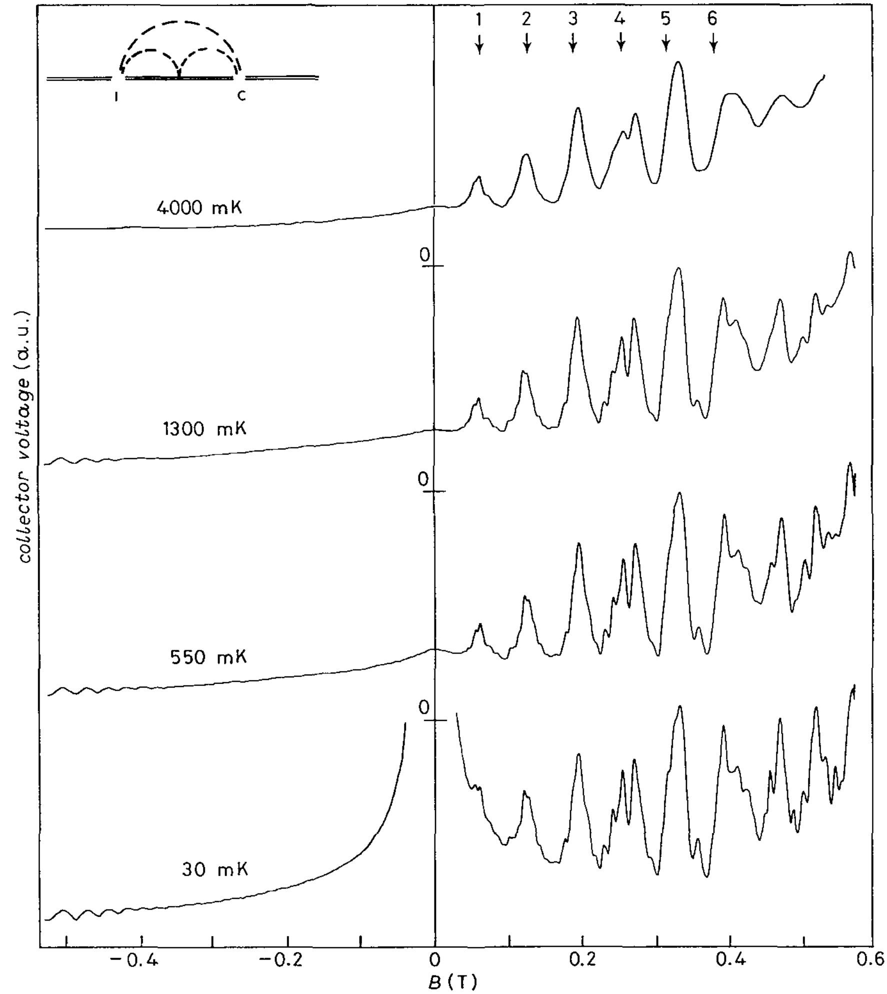

Fig. 2. – TEF spectra for $2W/\lambda_F \sim n_c = 1$ at temperatures between 4 K and 30 mK. Peak positions according to eq. (1) are indicated by arrows. The inset illustrates typical trajectories for the first and second maxima. At low temperatures in reverse field, small Shubnikov-De Haas oscillations appear and, on a different field scale, fine structure in the TEF spectrum is resolved. (The large negative peak around $B = 0$ is a series magnetoresistance effect, see (1).)

The Fermi wave vector is obtained from the carrier concentration by $k_F = \sqrt{2\pi n_s}$. The observed peak spacing at 4 K agrees within the experimental uncertainties with the value predicted by eq. (1), as indicated by arrows in fig. 2. The electron focussing spectra in fig. 2 firmly establish that ballistic injection of 2*D*-electrons has been realized in this experiment. For reverse values of the magnetic field no peaks are observed, which is as expected because of the simple Fermi circle in a 2DEG in GaAs-AlGaAs heterostructures. (In metals more complicated Fermi surfaces can give rise to peaks for this field direction as well [5]). The large number of maxima observed indicates that the reflections from the 2DEG boundary are predominantly specular. A similar conclusion has been reached in our recent analysis of the modification of the field scale of weak localization in high-mobility electron gas channels [8]. Note that the electron gas boundary is a depletion potential wall confining the electron gas. Specular scattering of waves occurs if the wavelength is large compared to

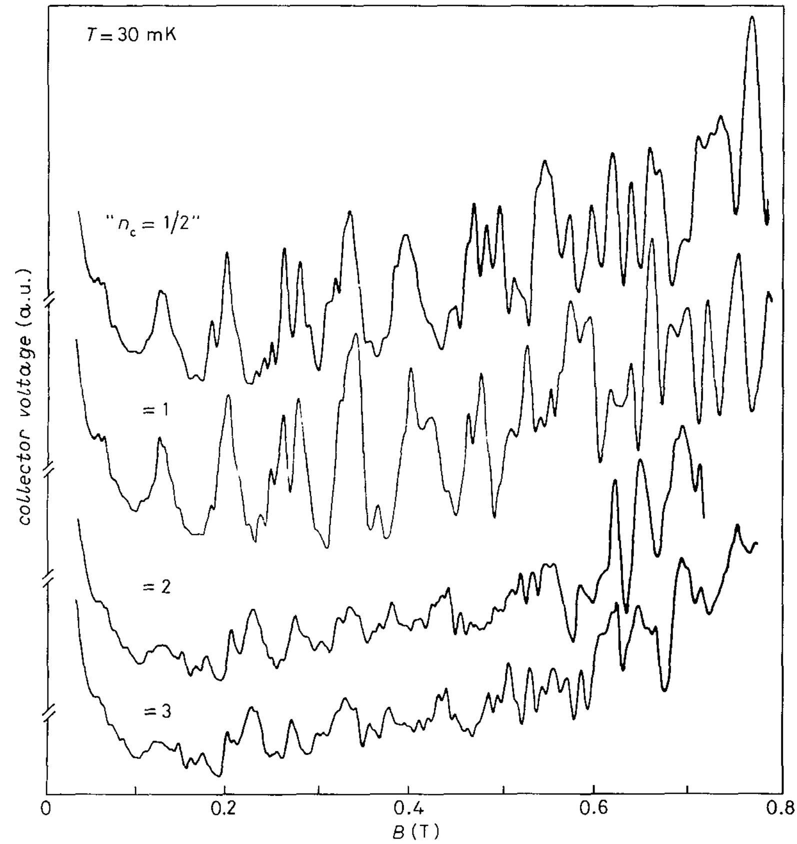

Fig. 3. – Dependence of the TEF spectra on the channel number $n_c \sim 2W/\lambda_F$ at 30 mK.

the surface irregularities, which condition is rather easily met in our case because λ_F is so large (~ 40 nm). Beyond fields of about 1.5 T no clear focussing spectrum is observed. For very high fields essentially all electrons enter the collector, and eventually quantum Hall plateaux are seen.

At low temperatures [1] an unexpected, reproducible fine structure develops in the TEF spectra (see fig. 2), if the voltage drop over the injecting point contact is kept sufficiently low. The possible origin of the fine structure will be discussed below. We first turn to the influence of the constriction width on the TEF spectra. The width of both point contacts is simultaneously changed by varying the gate voltage. For classical ballistic ($l \gg W \gg \lambda_F$) point contacts in a 2DEG the width follows directly from the conductance G according to $G = (2e^2/h)\, k_F W/\pi$. As described elsewhere [9], the behaviour of quantum point contacts deviates in an interesting way from this classical formula, in that plateaux in G as a function of W are observed. The conductance plateaux have been found to be integer multiples of $(2e^2/h)$. It is argued in ref. [10] that this quantum effect is associated with quantization of the transverse momentum in the constriction. In a plateau region the conductance is given by $n_c(2e^2/h)$, with n_c the largest integer smaller than $k_F W/\pi$. If quantization can be ignored

[1] The large central negative magnetoresistance peak seen at 30 mK is unrelated to the focussing, but is an artifact caused by the series resistance in the current carrying common ground contact. This specific problem is avoided if the collector voltage is measured with respect to a separate ohmic contact to the 2DEG (see fig. 1). The potential of this contact is not well defined, however.

($n_c \gg 1$), the classical result for G is recovered. Under the conditions of our electron focussing experiment n_c is a small number, so that the quantum nature of the point contacts may be important. The width of the quantum point contacts can be estimated from the conductance using the approximate relation $n_c \sim k_F W/\pi = 2W/\lambda_F$. In fig. 3 electron focussing spectra at 30 mK for various values of n_c are shown. An increase of n_c clearly leads to a smearing of the spectra, presumably as a consequence of the loss in resolution as the collector becomes wider. The positions of the fine-structure peaks are essentially unchanged.

The fine structure observed in the TEF spectra is not simply related to magnetic quantization of the bulk density of states [10]; the fine structure develops at lower fields than the Shubnikov-De Haas oscillations observable in the reverse field signal, and also the peak separation is different (see fig. 2). Since the fine structure is absent in the reverse field signal, it must be related to the focussed electrons. Also we did not observe any fringes in the two terminal magnetoresistance of a single-point contact.

We are not clear about the origin of the low-temperature fine structure in the TEF spectra. Tsoi [11] has observed in bismuth a much less pronounced fine structure in the first classical focussing peak only. He has attributed this to the quantization of skipping orbits [12]. We are currently investigating whether such quantization can account for our experimental data. Additionally, quantum interference between different trajectories may play a role.

In conclusion we have observed transverse electron focussing in a two-dimensional electron gas by the ballistic injection of electrons through small point contacts of adjustable width. At low temperatures large fine structure is found.

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